A Compact Short-Pulse Bremsstrahlung Source from LWFA Electrons

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Introduction

Since their inception, short-pulse lasers have been used to time-resolve ultra-fast phenomena. Using the short burst of visible light as a gate, temporal information may be gleaned from fast processes including the arrival of shocks at opaque boundaries [1] and wakefield imaging on the femtosecond scale [2] for example. Direct use of the laser, limits the accessible probing environment to regions in which the laser may propagate such as surfaces and low-density gases and plasmas. In order to probe to higher density, x-rays may be generated from the laser by either pumping an atomic transition such as the K-alpha line [3] via laser-generated fast electrons, or using wakefield accelerated fast electrons to produce bremsstrahlung radiation in a thick secondary target [4]. If the former method uses the K-alpha line then the radiation may be prompt and so on the order of the laser duration, but the radiation is emitted isotropically and from a relatively large source. The latter may be directional but the thickness of the secondary target results in an increase in both the radiation source size and x-ray pulse duration. Here we present results from an experiment where wakefield accelerated electrons are used to generate bremsstrahlung radiation in a thin (100 µm) foil. While the reduced thickness of the foil decreases the efficiency of radiation generation, it does allow both the source size and pulse duration to remain small (< 20 µm; < 50 fs) since multiple scattering events are unlikely.

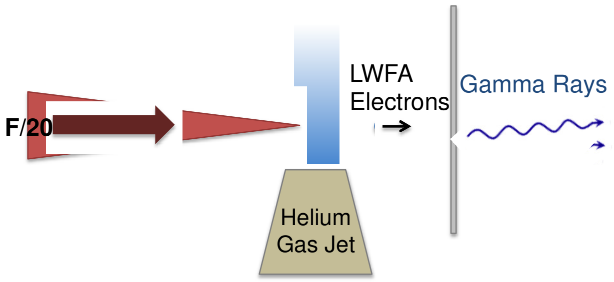

Fig1: Experimental Setup

Experimental Setup

The south beam of Astra Gemini is focused with a long focal length (F/20) off-axis parabola to a focal spot of around 28 µm (FWHM) onto the rising density gradient of a helium gas jet. The focal spot contained about 40% of the 12J available and was delivered in 44 fs resulting in a peak intensity of approximately 1.8×10^{19} Wcm^{-2} ($a_0 = 2.9$). The gas is fully ionized by the prepulse or rising edge of the laser to an electron density of 7 x 10^{18} cm^{-3}. The main pulse then drives a wakefield in this plasma capable of generating a single quasi-monoenergetic electron bunch [5]. The electron bunch leaves the wakefield and passes through an aluminium foil placed some distance behind the gas jet in order to generate the short-pulse bremsstrahlung source. The geometry of the experimental setup is sketched in Fig. 1. Directly after the radiator foil, the electrons are deflected off-axis by a permanent magnet, and pass through two Lanex screens which fluoresce in response to the electrons. The position of the resultant fluorescence is recorded by a 16-bit Andor iXon EMCCD camera in order to measure the electron energy, and the divergence in one of the transverse directions. The bremsstrahlung gamma rays leave the vacuum chamber (which acts as a filter for lower energy photons) and strike an array of caesium iodide (CsI) scintillators (approximately 5 x 5 x 30 mm each), the luminescence from which is recorded on a CCD which views the square faces of the cuboid scintillators. The scintillators are held in place by a punched aluminium sheet, causing them to appear circular. This geometry is shown in Fig. 2.

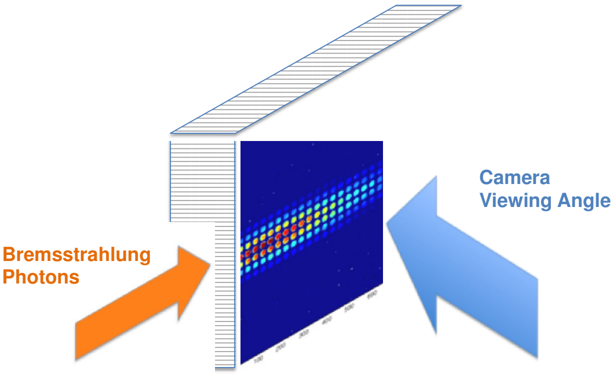

Fig2: Geometry of the CsI array detector and CCD camera relative to bremsstrahlung source

Geant4 Simulations

Geant4 [7,8] is a package used to simulate the passage of particles through matter, using Monte Carlo methods to model their interactions. Detailed modelling of the target chamber and detector geometries, combined with physics lists to suit the interaction energies, was used to obtain an accurate response from the scintillator array. Furthermore, electron spectra obtained experimentally were used as inputs for greater accuracy still. In each case, 2.5 million events were generated by Geant4.

Two output plots were produced by the simulation: The first shown in Fig. 3(b) is a spectrum showing the number of photons produced for a given energy. This plot has been scaled in order to represent the real number of electrons in 3(a) rather than the 2.5 million events simulated. The second, Fig. 4(b), is a 2D plot of the response of the scintillator array showing the total energy deposited in each CsI block.

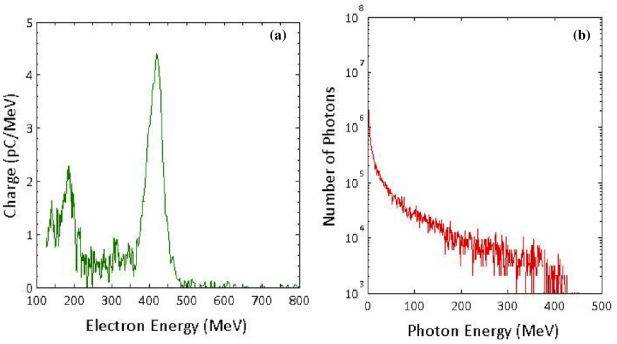

Fig3: (a) Experimental Electron Spectrum; (b) Calculated Photon Spectrum

Experimental Results

Figure 3(a) shows the electron spectrum from a typical shot. Most shots generated a monoenergetic electron bunch with 10 – 100 pC of charge and a peak energy between 350 and 600 MeV. Figure 3(b) shows the bremsstrahlung spectrum calculated using the Geant4 Monte Carlo simulation package. This run of the simulation modelled the passing of the measured electron spectrum through the foil.

Figure 4(a) shows the recorded signal from the CsI detector stack on the same shot. The FWHM of the gamma pulse at the CsI approximately 15mm equating to a divergence of around 5 mrad. The electron spectrometer shows that the electron divergence is also around 5 mrad. Since the electrons passing through the foil and the bremsstrahlung gamma rays have the same divergence, the maximum angle between any electron and its bremsstrahlung photon is 5 mrad. This geometric effect can only be responsible for stretching the photon pulse by less than 1 fs, so we assume that the bremsstrahlung pulse duration is equal to that of the electron bunch. Figure 4(b) shows the response of the scintillators as calculated by Geant4 considering the measured electron spectrum and the geometry of the chamber. These images are currently scaled independently to demonstrate the qualitative agreement, but future work will aim at generating plots which will compare the experiment and simulation quantitatively.

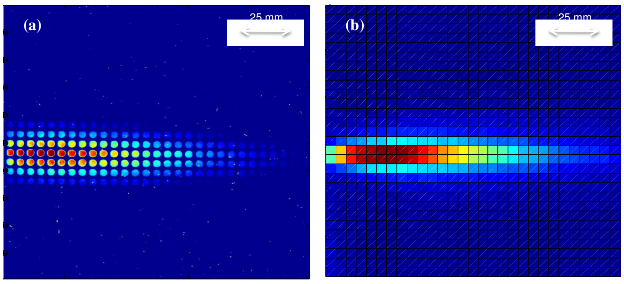

Fig4: (a) Image of CsI detector recorded by the CCD camera from the experiment; (b) Image of CsI detector generated by Geant4

Calculation of photon flux

Since the electrons are relativistic, and the CsI detector shows that the bremsstrahlung measured is approximately collinear with the electrons, the duration of the bremsstrahlung is dictated purely by the duration of the electron bunch. PIC simulations (validated by experiment [6]) indicate a LWFA electron bunch of this type will be around 30 fs in duration and have a beam waist of around 20 microns. Using the photon number spectrum calculated by Geant4 and scaled for the measured number of electrons, the peak power of the gamma pulse is ~5 GW. The geometric emittance is estimated to be around 0.1 mm mrad.

Conclusions

We demonstrate a short pulse, low divergence gamma ray source generated from LWFA electrons with relative simplicity. The source has a geometric emittance of ~0.1 mm mrad, a pulse duration of ~30 fs and a peak power of around 5 GW.

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